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Bridge Deck Condition Surveys Using the DART Prototype Vehicle

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Bridge Deck Condition Surveys Using the DART Protype Vehicle

Authors:	T. Masliwec D.G. Manning
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MTO Contact	T. Masliwec, (416) 235-4689
Abstract:	Research studies were undertaken to develop methods for the rapid and automatic collection of data on the condition of bridge decks. The result of these studies was the DART (Deck Assessment by Radar and Thermography) system. As the acronym implies, DART utilizes two basic systems: impulse radar, and infrared thermography. Testing of a prototype DART system was undertaken during the period of May to October, 1986. Field evaluations were carried out on overlaid and non-overlaid bridge decks. The findings demonstrated that the DART prototype is an effective system for identifying the location and type of concrete deterioration in bridge decks, with or without a bituminous surfacing. It is envisaged that DART will develop into a routine, rapid, non-contact and non-destructive method for surveying the condition of bridge decks. The system will then be used to support MTO's bridge management program.
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T. Masliwec
Research Scientist
Materials Research Office
Research and Development Branch

D.G. Manning
Principal Research Engineer
Materials Research Office
Research and Development Branch

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The Editor, Technical Publications
Ministry of Transportation
1201 Wilson Avenue
Downsview, Ontario
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Telephone: (416) 235-7635
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1/ Introduction

An effective bridge management system requires a comprehensive data base. At the network level, the data are needed in order to assess the overall condition of the bridge network and to predict the effect of alternative preservation and improvement actions [1]. At the project level, more detailed data are required to select the most appropriate method of rehabilitating a particular structure and to prepare the contract documents.

Collecting data on the condition of bridges by traditional methods is expensive and the results are not always reliable. In the mid 1970's, research studies were initiated to develop methods for the rapid and automatic collection of data on the condition of bridge decks. The studies were part of a much larger program to improve the technology for rehabilitating bridges. The initial focus of the program was on decks.

A number of techniques were investigated over a period of almost ten years [2,3] and the product of the work was the DART (Deck Assessment by Radar and Thermography) system [4]. As the acronym implies, DART utilizes two basic systems: impulse radar, and infrared thermography.

This paper describes the main features of the DART system and summarizes the results of testing the prototype unit under field conditions during the period May to October, 1986.

2/ Major Types of Deterioration in Bridge Decks

The most serious form of deterioration is that caused by corrosion of embedded reinforcement. As the reinforcement steel corrodes, it expands and creates a crack or subsurface fracture plane in the concrete at, or just above, the level of the reinforcement. The fracture plane, or delamination, may be localized or may extend over a substantial area.

Scaling, which is a breakdown of the cement-paste matrix, is also a serious problem wherever it occurs. The disintegration of the concrete, which is caused by the freezing of concrete critically saturated with water, begins at the surface and gradually progresses so that the full depth of deck slab may be affected.

On asphalt-covered decks, bond failure may occur between the concrete deck and bituminous surfacing. Debonding can result in moisture being trapped on the surface of the concrete and, where thin surfacings are used, can lead to failure of the bituminous surfacing. Although the consequences of debonding are not as serious as either delamination or scaling, it can be confused with these two phenomena in surveys. Consequently, it is important to be able to identify and define debonded areas.

3/ How Thermography and Radar Detect Deterioration

Infrared thermography is a remote method of measuring the surface temperature of an object. Consequently, the detection of deterioration by infrared thermography is based on the difference in surface temperature that exists between deteriorated and sound concrete under certain atmospheric conditions. The surface temperature differences develop as a result of different rates of heat transfer occurring from the surface inward. The surface, while being irradiated with solar radiation, is presumed to receive a uniform heat flux. Anything which impedes the conduc-

tive heat flow from the surface, such as a delamination or debonding, will result in a higher surface temperature during periods of heating. The reverse is true during periods of cooling, mainly at night. Because of the breakdown of the matrix, scaled concrete has a different coefficient of thermal conductivity than sound concrete and this also results in a difference in surface temperature.

The detection of deterioration by radar is based on reflections of a high frequency electromagnetic wave caused by changes in the electromagnetic properties of the material being probed. Whenever a transmitted wave encounters an electromagnetic discontinuity (deterioration) or change of material dielectric, it is partially reflected. The patterns created by the reflected waves are received by the radar antenna. The radar receiver takes a measurement of the time required for the transmitted pulse to travel to a target discontinuity and for the reflected pulse to return [4]. The time delay of the radar echo from a structural discontinuity is directly related to the depth of the fault.

Echoes are received from the surface of the pavement, the boundary between the asphalt overlay and the concrete deck, the rebars within the deck, and from the bottom of the deck, as shown in Figure 1. Concrete delamination tends to occur within the region between the asphalt concrete interface and the first layer of rebars. This typically gives rise to an increase in signal amplitude at the depth where delamination occurs [5], as depicted in Figure 2. Figure 3 shows a radar waveform from a sound region of bridge deck. The time separation between peaks or echoes enables the thickness of a layer of material or the depth of a structural flaw to be calculated from a knowledge of the dielectric constant for each material. For example, in Figure 3, the time separation between the first two positive peaks is directly related to the asphalt overlay thickness.

4/ The DART Prototype Unit

The DART prototype unit was designed to incorporate both a radar and infrared system with their respective peripherals. A vehicle was dedicated to the system and is shown in Figures 4 and 5.

4.1/ Radar

The equipment configuration is illustrated in block form in Figure 6. The radar unit is a short pulse, high resolution system employing a monostatic antenna. The radar transmits an electromagnetic pulse, approximately one nanosecond in duration, with a pulse repetition rate of 5 MHz. A wide bandwidth, low loss, matched antenna is used to transmit the electromagnetic energy and to receive return signals. The radar antenna, transmitter, and receiver are mounted on a sliding bracket attached to the front bumper of the DART van. The antenna is mounted at a height of 150 mm above the deck surface. At this height , the antenna has a ground surface coverage pattern of about 0.4 m^2 in the shape of an ellipse 300 mm by 175 mm. Returning radar echoes are received by the antenna, and transmitted to the control unit inside the vehicle. The waveform is simultaneously displayed on an oscilloscope and recorded on a seven-channel FM tape recorder. The operator can monitor the signal from the control unit and from the tape recorder, thus permitting a check of the quality of the signal before and after recording.

The trigger pulse for the system, a filtered version of the waveform and three sets of distance information are recorded for analysis using a microcomputer. The radar itself is battery powered and has an operating time of 6 hours per charge.

The fifth wheel, which is mounted on the left rear of the van, outputs a signal which is sent through an interface to produce three sets of distance pulses. Each of these pulses is used in processing of the radar data for various program options, using custom software.

4.2/ Infrared

An infrared scanner is mounted to a rack connected to the DART vehicle, as shown in Figure 4. The infrared system senses energy emitted from the deck surface in the 3 to 5.6 micron range using an indium antimonide (InSb) detector. It has a sensitivity of approximately 0.1°C. Scanners which detect in a longer wavelength range have a lower signal-to-noise ratio and less resolution than the shorter wavelength equipment. At a height of 4.5 m, and adjusted at an oblique angle of 45°, the scanner (when equipped with a 20° lens) is capable of scanning one complete traffic lane width in a single pass. The scanner is connected through a scanner control unit to an interface unit which converts the scanner's European standard (PAL) signal to the North American (NTSC) standard. The output of the interface is then fed to a high resolution video tape recorder. A schematic of the infrared system is shown in Figure 7.

The operator monitors the raw infrared image on the scanner control unit in an effort to optimize the controller gain. The operator can also review the video tape to ensure that the image recorded is comparable to what was observed on the infrared monitor, and check that the appropriate fifth wheel distance information is present. The output of the fifth-wheel is recorded on one of the audio channels on the video recorder and is used to identify the longitudinal position on the deck when the data is processed.

For processing the data, the video record is fed into an on-board computer through an image digitizer interface. Using custom software, the infrared image is sampled in such a way that the oblique angle of view and other distortions of the infrared image are eliminated. Deterioration is identified through a combination of computer and operator assisted machine interpretation [6]. The computer produces a scaled graphics image of each lane of the deck, showing areas of delamination and scaling. Debonding is only identifiable if it covers large areas of the deck. This hardcopy information can then be used in conjunction with the radar data to permit a comprehensive assessment of the condition of the deck.

5/ Field Experience

The DART prototype unit was used to investigate the condition of several bridge decks during the period May to October, 1986. In addition, the infrared equipment was rented for one week in February to investigate its application during cold weather.

The results of those investigations are discussed in general terms for all bridges and with respect to three specific bridges which illustrate different operational characteristics of the system. The three bridges were:

- the Winston Churchill bridge, an old asphalt-covered slab-on-beam structure,
- the Hogg's Hollow bridges, thin slab bridges located on a freeway which were overlaid with latex-modified concrete in 1979; and
- the MacDonald-Cartier bridge, also a thin slab bridge but with a thin bituminous surfacing.

The vehicle is operated at a speed of between 3 and 4.5 km/h. At faster speeds, the digitized version of the infrared image is distorted and the radar surface coverage capability is impeded.

Whereas one pass with the equipment permits an infrared scan of one complete lane width, the radar collects information only along a grid line approximately 300 mm wide. The number of grid lines required with the radar is a function of the condition of the deck (the worse the condition of the deck, the more grid lines are needed). In general, on a typical two-lane bridge, three passes were made in one traffic lane, and two in the other lane, as shown in Figure 8. The data were analysed using a "quick-look" version of the software which samples data every 10 m along each grid line and the processing is completed in a few minutes. If the "quick-look" program indicates significant deterioration, additional passes are made and, on badly deteriorated decks, a grid-line spacing of as little as 1 m may be used. The "quick-look" program also enables the operator to verify the quality of the data.

Traffic protection and lane closures are required for the safe operation of the DART equipment. The extent of the traffic protection and the number of lanes closed at any one time, depends upon specific site conditions. Usually, the more extensive the closure, the faster the survey can be performed. On a typical two-lane bridge with a heavy volume of traffic, the time taken to set up the traffic protection usually exceeds that taken to complete the infrared and radar surveys.

For the purposes of discussing the operating characteristics of the prototype unit, it is convenient to describe the experience gained with the infrared thermography and the radar separately.

5.1/ Infrared Thermography

To assist in the identification of the lanes of the bridge deck, thermally reflective markers, consisting of a 300 mm circle and a 300 mm square flat reflector, are placed on the bridge deck prior to each survey. The circle is placed at the intersection of the lane marker and the expansion joint on the south or west end of the bridge. The square marker is placed at the next expansion joint, typically at the opposite end of the bridge deck adjoining the road. This placement of the marker facilitates the image processing.

During periods of heating, delaminated areas of a bridge deck appear as white or hot areas (through an infrared camera), compared to undelaminated areas which are dark or cool areas. In general, the greater the temperature differential between sound and unsound deck, the easier it is to detect delaminations using an infrared camera. A typical infrared output for a delaminated deck is shown in Figure 9.

Scaling of the concrete below asphalt produces a characteristic thermal image which is a mottled grey-white tone. The more severe and extensive the scaling, the more mottled the thermal image appears.

Debonding is not easily identified by infrared thermography. The debonding at times appears to be hotter than adjacent delaminations. Depending on the thickness of the delaminations, the debonding can appear identical to delaminations, and, at other times may go undetected.

It soon became clear that infrared thermography cannot be used for this application if any form of moisture is present on the bridge deck. Precipitation preceding the survey day must also be taken into account. If water has accumulated in a delaminated area, it will act as a continuum for impinging solar radiation. Since water has a large latent heat of vapourization, most of the surface heat will be absorbed and transferred by the water. As a result, a delamination will not be detected by the infrared system. Two surveys performed on the Winston Churchill bridge illustrate this effect. On a hot day (32°C) with no wind, high irradiance, and no previous rain

(for at least six days), several delaminations were visible on the bridge deck. Three weeks later, on a cooler day (18°C) with no wind and high solar irradiance, several of the previously visible delaminations were not detectable. Upon closer examination, it was discovered that there was water underneath the asphalt surface, a consequence of rain during the previous three days. This means that not only must the weather conditions be favourable on the day of the survey, consideration must also be given to precipitation on days prior to the survey.

Operation of the infrared system should be limited to clear sunshine (or, at most, 10% cloud cover). Observed temperature differentials can reach 9°C on a very sunny day on asphalt-covered bridge decks or 5°C on exposed concrete decks. If clouds are present, the temperature differential between deteriorated and sound surfaces will not be as great and, therefore, will be more difficult to detect. All the effects of cloud cover on bridge deck heating have not been quantified, but the infrared energy will be reduced by the reduction in solar radiation. In addition, the reflected and emitted infrared spectrum must remain constant in subsequent infrared processing and mapping. If the solar irradiance is changing randomly, the recorded grey scale infrared images will change accordingly (fading in and out). This makes comparisons of different parts of a bridge deck difficult, as it is impossible to set a certain colour pixel to represent the deteriorated area. Therefore, clear sky conditions are required to be able to detect deck deterioration with confidence.

Previous studies [7] have indicated that high winds effectively neutralize bridge deck temperature differences, but that light winds have little effect. While wind velocity is an important component in theoretical calculations of bridge deck temperature differences [8], wind velocity was not a major factor during field trials. On several exposed concrete and asphalt-covered bridge decks, winds gusting to a maximum of 60 km/h under clear skies were recorded on an anemometer positioned 2 m above the deck surface. However, the relative temperature differences measured through the infrared system did not change because of this gusting. In addition, when steady winds up to 50 km/h were blowing during a survey of the MacDonald-Cartier bridge, deterioration was readily visible through the asphalt surfacing. From these observations, it is concluded that under clear sky conditions, wind velocities of up to 50 km/h will not affect infrared surveys significantly.

The optimum time for infrared operation (in southern Ontario) is from 10:00 a.m. to 11:00 a.m. on exposed concrete and 12:00 noon to 1:00 p.m. on asphalt covered bridge decks. At these times, the temperature differences between unsound and sound bridge deck areas are most easily distinguished. More importantly, however, the area of the hot spots best approximates the actual size of the deteriorated areas. In other words, even though the maximum difference in surface temperature usually occurs later in the day, the outline of the deterioration is less distinct under these conditions. Temperature differentials were found to exist at almost any time of the day except around sunrise and sunset. Around sunrise, the surface temperature of the deteriorated region changes from being cooler to hotter than the average deck surface temperature. The reverse situation occurs shortly after sunset.

For asphalt covered bridge decks, it is essential that the decks receive a reasonably constant amount of solar radiation before measurements are made. After about 3:00 p.m., the deck begins to cool due to reduced solar radiation. Under such conditions, the contrast between sound and unsound deck is reduced and, sometime before sunset, the temperature differentials become undetectable.

The optimum time of year for infrared bridge testing will depend upon local climate and latitude. In southern Ontario, maximum temperature differentials were observed in early or late summer when clear skies prevailed rather than in mid-summer when overcast conditions were

more prevalent. Ambient temperatures in the range of -33°C (in February) to 32°C were investigated and were not found to have a significant effect on the detectability of deterioration. Differentials were, however, greater in the summer than winter because of the greater intensity of solar radiation.

As a rule, delamination, scaling, and debonding can be detected when all asphalt surfacing is less than 75 mm thick. At greater thicknesses, the detection of deterioration becomes uncertain.

Although the equipment has a sensitivity of about 0.1°C, a temperature differential of 1.5°C to 2°C is a reasonable practical minimum to counteract the effects of differences in emissivity caused by such factors as polishing in the wheel tracks, staining, and patching.

Thermographs taken of the same deck on different days will not be the same. Not only will weather conditions not be precisely the same, but any change in the absorptivity of the deck surface (for example, rainwater removing dust) will also affect the thermograph.

Normal traffic density was not found to affect the infrared inspection technique significantly. Normal traffic on adjacent lanes did not influence the results. Transient shadows of large vehicles were observed at some sites but, these moved rapidly enough not to affect the infrared image. However, if the traffic density is sufficient to lower the solar irradiance reaching the deck surface, temperature differences are affected. Such a condition existed during the survey of the Hogg's Hollow Bridges where lane closures resulted in bumper-to-bumper traffic in the lanes which remained open. When the traffic protection was changed to allow the survey of the lanes subject to heavy traffic, delaminations were not readily identified and, between the wheel tracks there was a noticeable heating effect from the engines of slow-moving vehicles.

Accumulations of debris on the surface, particularly sand remaining from winter maintenance operations and concentrated near the curbs, will affect infrared surveys. If this condition exists, the bridge deck should be swept the day before the actual survey.

Infrared surveys should always be performed before radar surveys. This is because any obstructions to solar radiation on the bridge, such as people or stationary vehicles, can cause false readings in the infrared image.

The amount of time required to affect the surface of the deck is usually less than one minute in full sun, clear sky conditions. Consequently, the operator must be aware of the effect of shadows cast by such items as signs and trees.

5.2/ Radar

The condition surveys during 1986 were used to assess the radar's operating characteristics under a range of climatic conditions on a variety of structures.

Water standing on the deck surface attenuates the waveform and effectively prevents reliable signal processing. However, dampness on the deck surface does not affect the reliability of the radar.

The major advantage of radar is the ability to propagate through layered media, thereby giving information on bituminous surfacings, concrete deck slabs, the interface between the two, and any discontinuities. In fact, a bituminous surfacing more than 25 mm thick enhances waveform interpretation (compared with an exposed concrete deck) because interference between the radar echo reflected from the deck surface and the radar echo from deterioration below the surface is reduced substantially. On exposed concrete bridge decks, reflected signals from defects interact with surface returns. The Ministry's existing software is applicable only to asphalt-covered bridge decks.

Typical radar output for a deck is shown in Figure 10. An "X" indicates delamination along each grid line. Similar outputs using a "D" to identify debonding and "S" to identify scaling are produced for the other types of deterioration.

Unlike the infrared system, radar has the advantage that it is virtually independent of weather conditions, and is well suited for use on asphalt-covered decks. It can also identify defects which cannot be detected by infrared thermography. However, it is less well suited for use on exposed concrete decks for the reason previously cited. The major disadvantage of radar is that it produces data along the lines which are traversed by the antenna. Consequently, unless several passes are made, areas of deterioration can be missed. On the other hand, infrared thermography can be used only when differences in surface temperature exist; however, it provides complete deck coverage. Its only real disadvantage is its dependence on the weather which is especially true for asphalt covered decks. A comparative evaluation of the relative strengths and weaknesses of the DART's radar and infrared systems is provided in Table 1.

It is apparent from Table 1 that the radar and infrared systems used in the DART prototype complement each other very well. Taken separately, the radar system provides only the dimension of depth, while the infrared thermography provides a two-dimensional surface image. By using both techniques, it is possible to obtain a three-dimensional perspective of the condition of a bridge deck.

6/ Costs

The DART system represents a significant investment. The value of the major items is summarized below; however, because of customs duties, fluctuations in exchange rates, and volatility in the price of electronic components, the following costs (in 1987 Canadian dollars) should be regarded as approximate:

Radar	$54,000
Thermal Scanner and Converter	$54,000
Microcomputer and Peripherals (including extra circuit boards)	$27,000
FM Recorder	$13,000
Industrial VCR	$ 5,000
Fifth-Wheel	$ 7,000
Oscilloscope	$ 2,400
Generator	$ 1,500

Adding the cost of the vehicle, trailer, external and interior racks and numerous smaller items such as cables, filters, and interface devices, would make the replacement cost of the fully equipped DART vehicle approximately $180,000. It should be noted the Ministry did not purchase the thermal scanner and converter, but rented the equipment during the summer months for $2,400 per month. In addition, the cost of developing the software was $96,000 for the radar and $30,000 for processing the thermal images.

7/ Concluding Remarks

The first year's experience with the DART system has shown that, within known limitations, the prototype constitutes a viable rapid non-contact and non-destructive method for performing condition surveys. At present, the DART prototype is not in a "push button mode" and requires a high level of skill and expertise to operate. However, even at this stage of development, it is realistically possible to perform 150 to 200 condition surveys a year. It is envisaged that the system will play a major role in providing data for the Ministry's bridge management system. In addition, the system will permit a reduction in the scope, and therefore a cost saving, in detailed bridge condition surveys which are made once a bridge is scheduled for rehabilitation. Furthermore, the opportunity to collect reliable data on the thickness of bituminous surfacings and the depth of cover in asphalt covered deck slabs affords an opportunity to simplify contract administration and lower prices by reducing the uncertainty in bid items.

8/ Future Research

Future work will depend largely on the experience gained in continuing use under operational conditions. Results will continue to be monitored to maintain confidence in the signal processing techniques by comparison with observed deck conditions. Other work will be undertaken to determine if the software can be adapted for processing signals from exposed concrete surfaces. Any other changes which are made are likely to focus on making the system simpler to operate and increase the durability of the components.

Other studies will be undertaken to determine the feasibility of applying radar to investigating the condition of other components of bridge structures and of pavements.

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Table 1/ Operational Characteristics of Radar and Infrared Thermography

OPERATIONAL CHARACTERISTIC	EFFECT	
	RADAR	INFRARED
Meteorological limitations	Adversely affected by standing water only	Need sun, low wind velocity. Inoperable with standing water.
When can system be used?	Year round	Year round but must have sun and no rain
What hours of the day can system be used?	All day	Ideally 9:00 to 15:00
Influence of external parameters:		
- paint markings	- none	- easily compensated for
- isolated debris	- none	- easily compensated for
- oil stains	- none	- easily compensated for
- skid marks	- none	- none
- snow/ice/water	- adverse	- adverse
- traffic	- none	- adverse if solar irradiance affected
Signal noise level	Waveforms need careful monitoring and calibration	Hot spots may not be detected due to meteorological factors or secondary reflections
Signal reproducibility	Independent of time, excellent	Dependent on solar heating, variable
Selectivity:		
- Asphalt covered deck	- Excellent results with overlay >25 mm	- Good if <75 mm overlay
- Exposed concrete decks	- Signal processing software not applicable	- Excellent results
Penetration	Detects deep seated effects; difficulty with surface effects	Detects only surface effects; no penetration
Surface preparation	None	Monitoring of solar obstructions. Surface cleaning may be required
Inspection speed (limiting factors)	Maximum 8 km/h (pulse repetition rate)	Maximum 4.5 km/h (video digitization rate/-camera scan rate)
Number of scans required	Many, depending on bridge width and coverage required	One scan per lane
Support personnel required	High level of technical competence	Basic training plus experience on bridges
Traffic protection	Necessary	Necessary

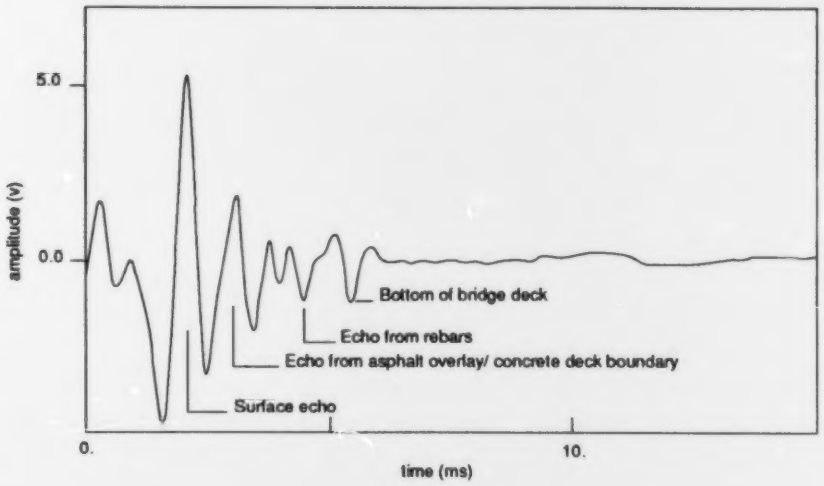

Figure 1/ Cross-section of bridge deck with corresponding radar signal

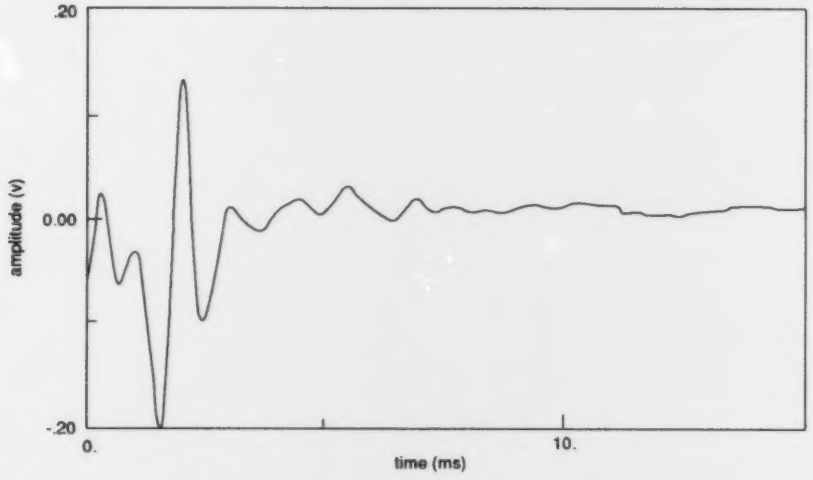

Figure 2/ Radar waveform for a region with delamination

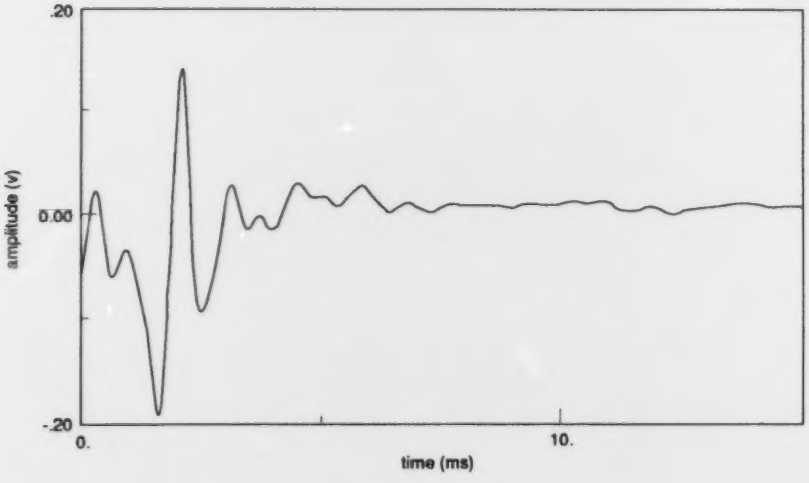

Figure 3/ Radar waveform from an area of good structure

Figure 4/ Exterior of DART vehicle

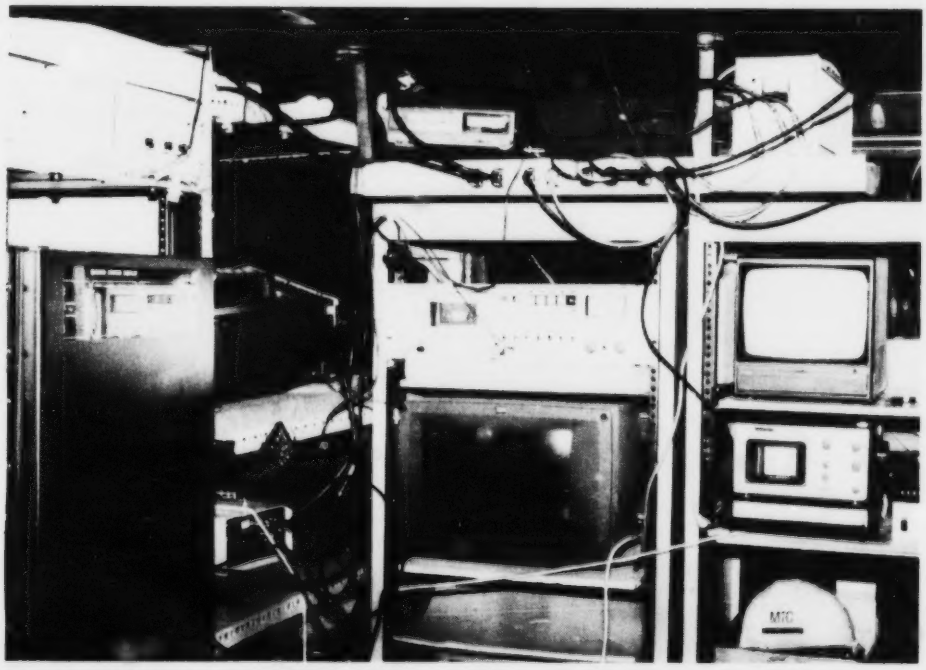

Figure 5/ Interior of DART vehicle

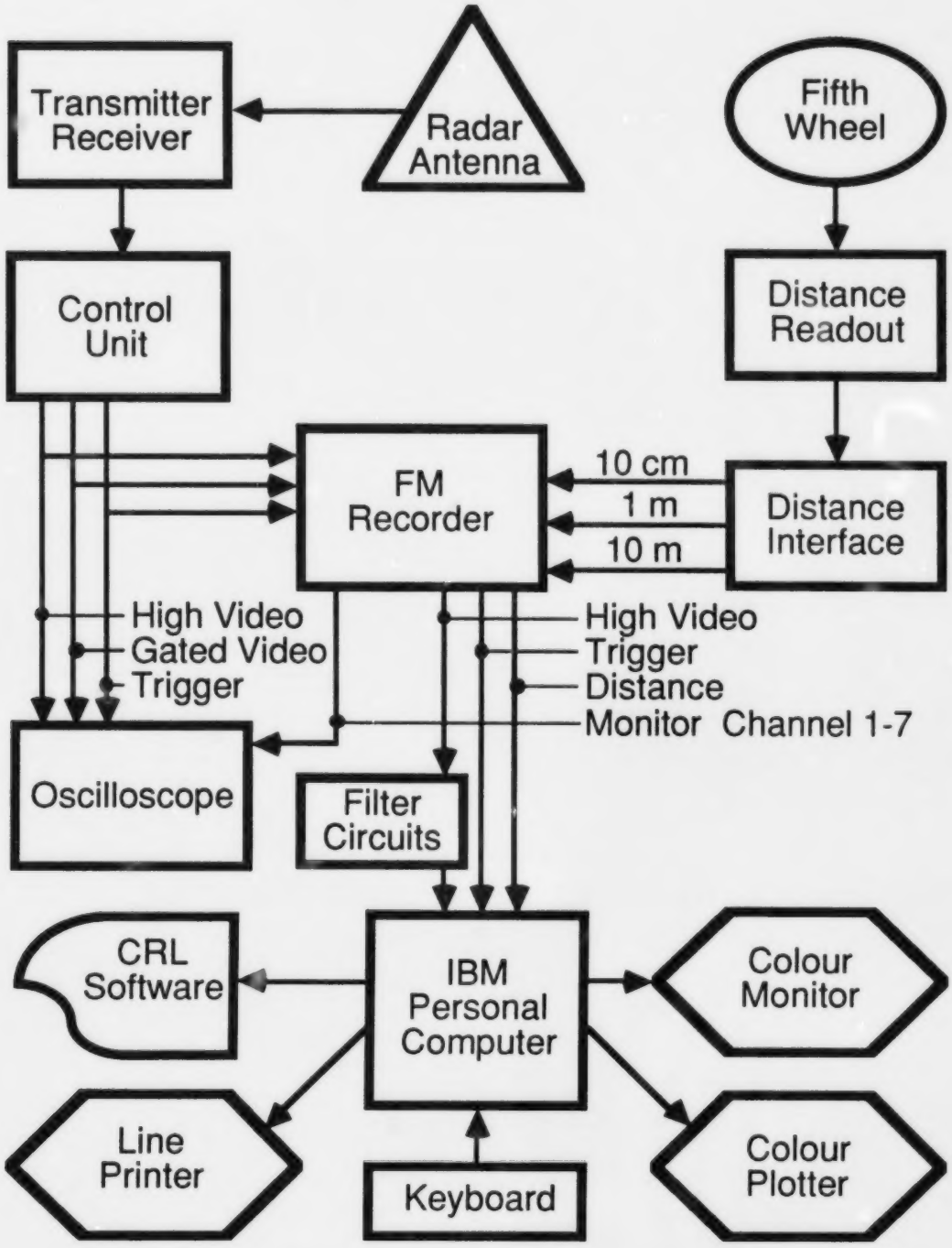

Figure 6/ Radar schematic

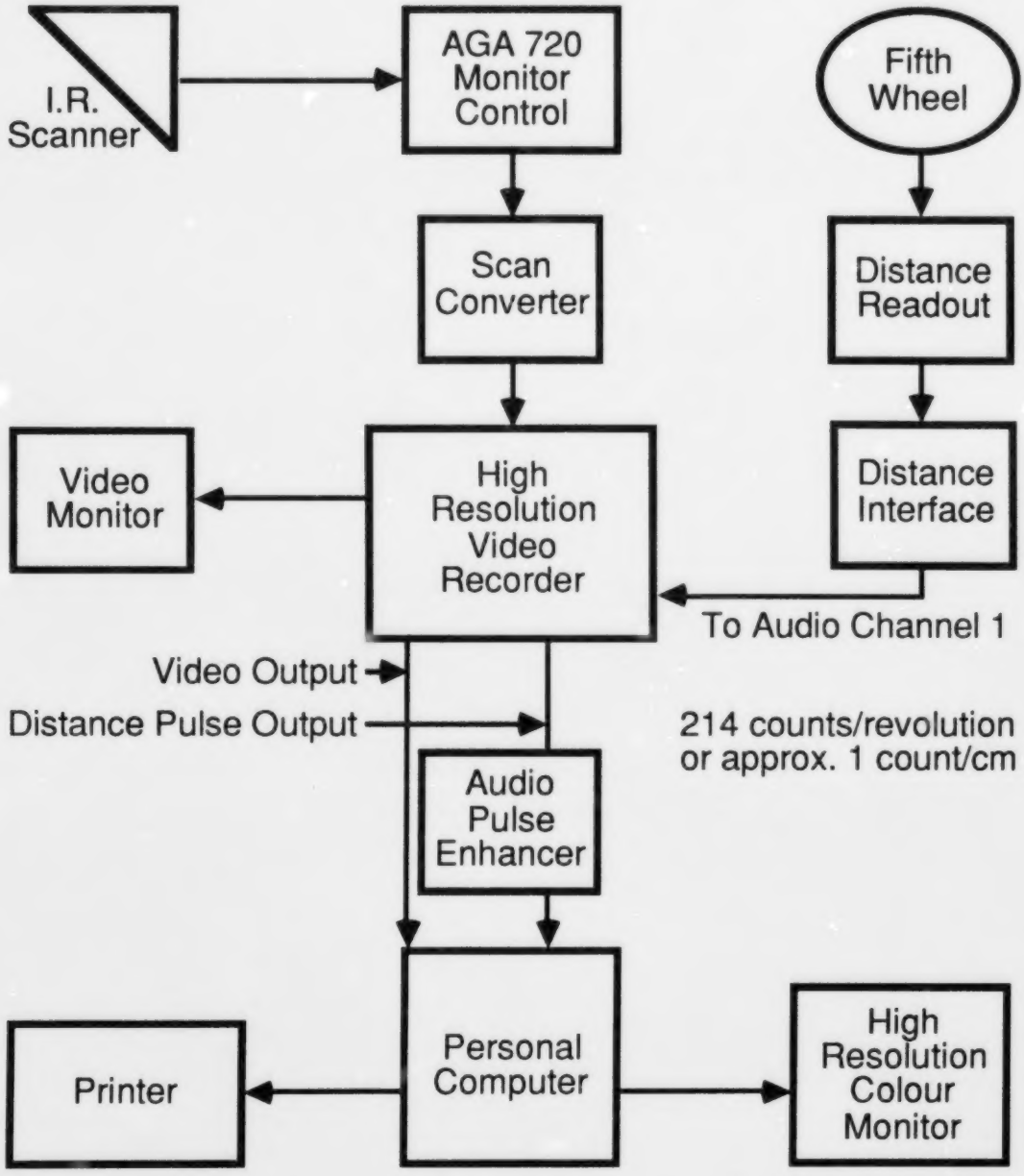

Figure 7/ Infrared schematic

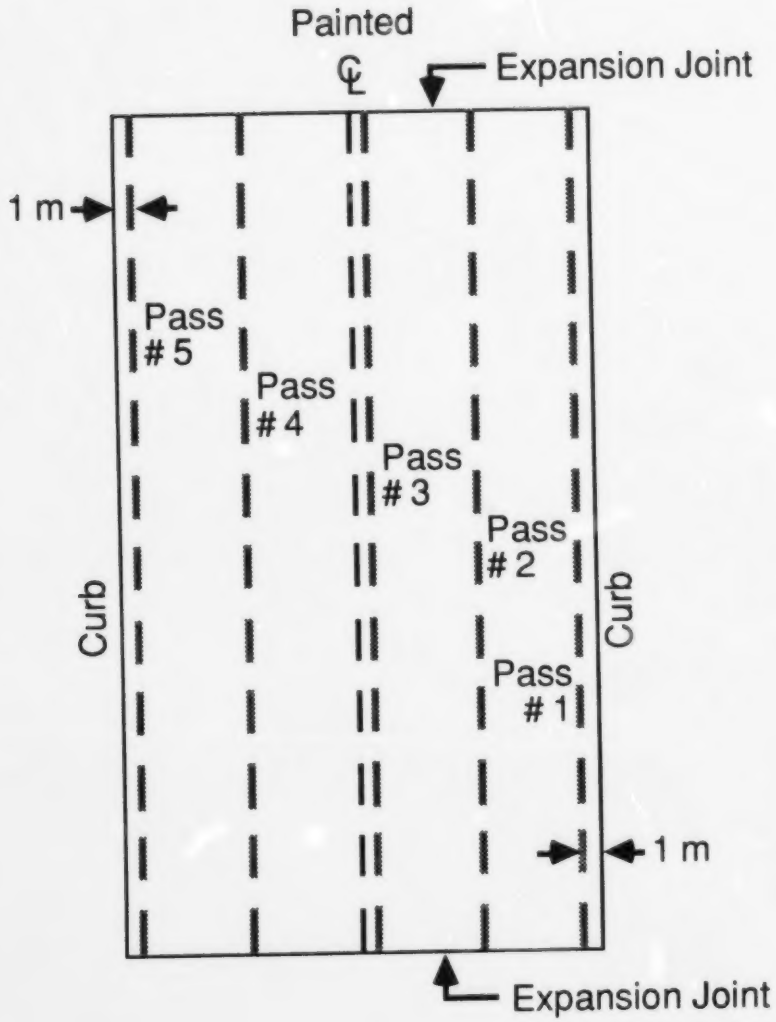

Figure 8/ Typical radar pass layout for a two-lane bridge

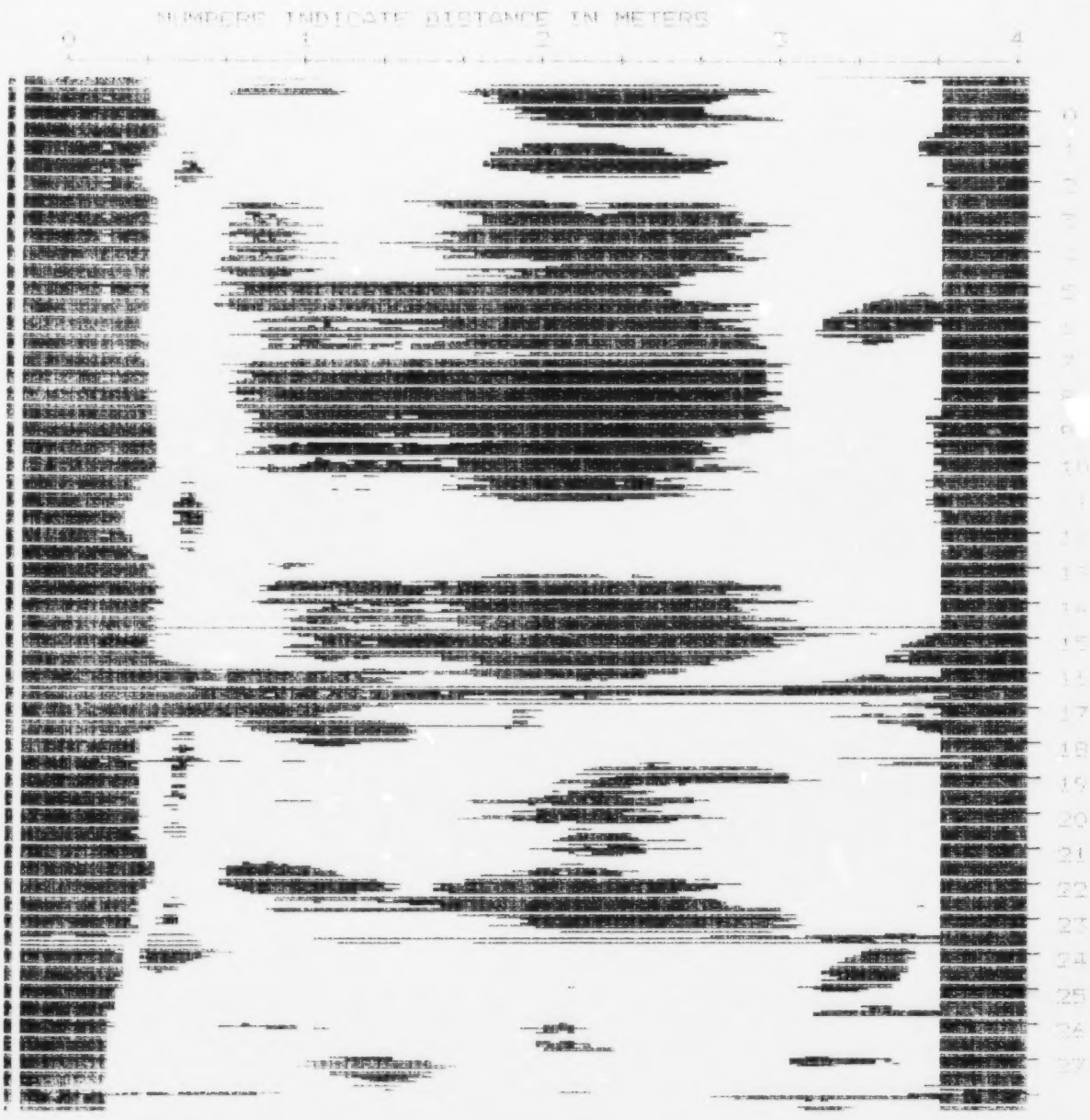

Figure 9/ Infrared output for a portion of one lane (Dark areas are delaminations)

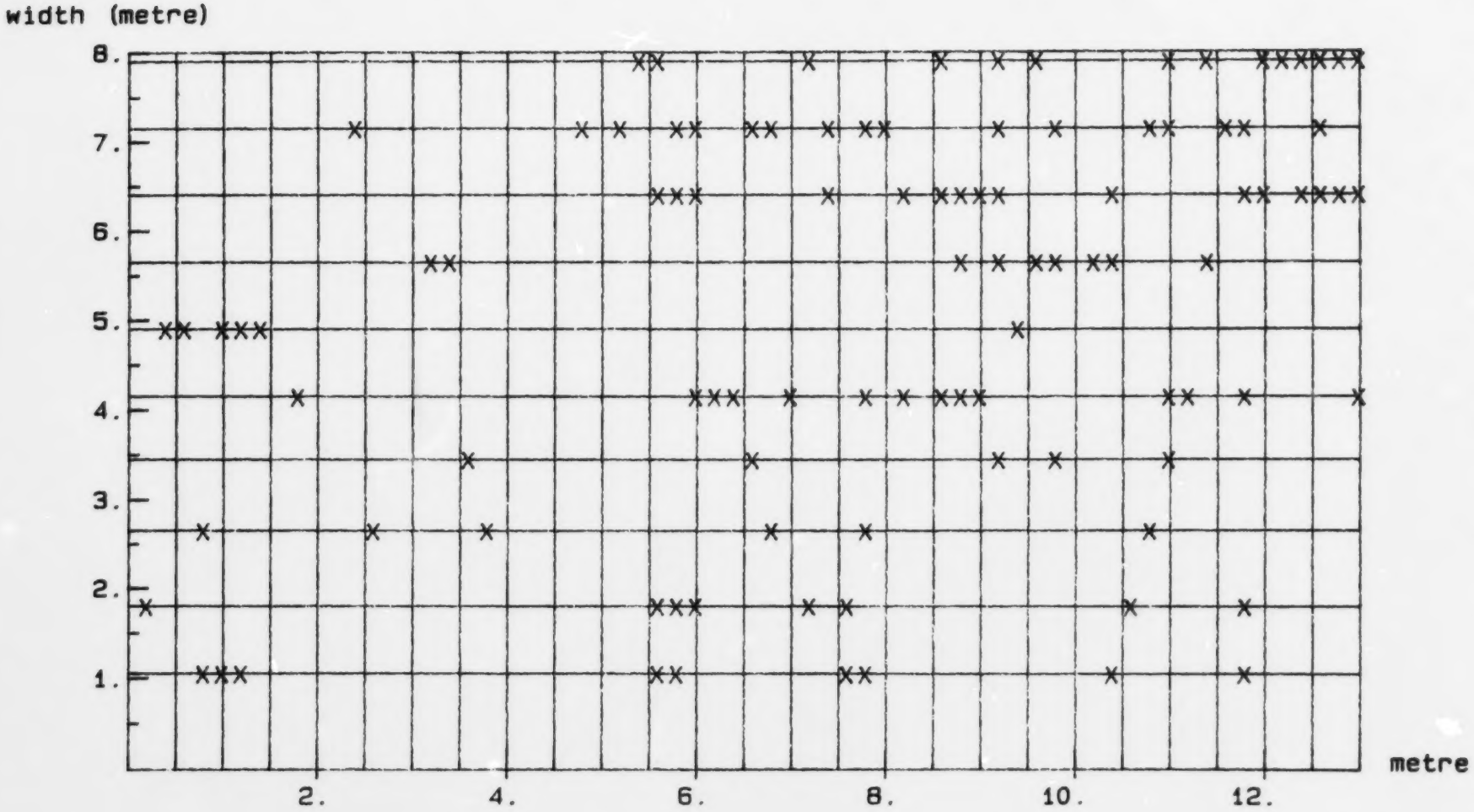

Figure 10/ Typical radar output